LLNL-JRNL-454031

LAWRENCE LIVERMORE NATIONAL LABORATORY

A three wavelength scheme to optimize hohlraum coupling on the National Ignition Facility

P. A. Michel, L. Divol, R. T. Town, M. D. Rosen, D. A. Callahan, N. B. Meezan, M. B. Schneider, G. A. Kyrala, J. D. Moody, E. L. Deward, K. Widmann, E. Bond, J. L. Kline, C. A. Thomas, S. Dixit, E. A. Williams, D. E. Hinkel, R. L. Berger, O. L. Landen, M. J. Edwards, B. J. MacGowan, J. D. Lindl, C. Haynam, L. J. Suter, S. H. Glenzer, E. Moses

September 9, 2010

Physical Review E

Disclaimer

A three wavelength scheme to optimize hohlraum coupling on the National Ignition Facility

P. Michel,[1] L. Divol,[1] R. P. J. Town,[1] M. D. Rosen,[1] D. A. Callahan,[1] N. B. Meezan,[1] M. B. Schneider,[1] G. A. Kyrala,[2] J. D. Moody,[1] E. L. Dewald,[1] K. Widmann,[1] E. Bond,[1] J. L. Kline,[2] C. A. Thomas,[1] S. Dixit,[1] E. A. Williams,[1] D. E. Hinkel,[1] R. L. Berger,[1] O. L. Landen,[1] M. J. Edwards,[1] B. J. MacGowan,[1] J. D. Lindl,[1] C. Haynam,[1] L. J. Suter,[1] S. H. Glenzer,[1] and E. Moses[1]

[1]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[2]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

By using three tunable wavelengths between cones of beams on the National Ignition Facility, numerical simulations show that the energy transfer between beams can be tuned to redirect the light out of the target regions most prone to backscatter instabilities. These radiative hydrodynamics and laser-plasma interaction simulations have been benchmarked against large scale hohlraum experiments with two tunable wavelengths, and reproduce the hohlraum energetics and symmetry. We predict that using a third wavelength option could significantly reduce stimulated Raman scattering losses and increase the hohlraum radiation drive while maintaining a good implosion symmetry.

The indirect drive approach to inertial confinement fusion (ICF) relies on the efficient and well balanced energy deposition of multiple laser beams into the wall of a cylindrical cavity (the "hohlraum") [1]. The deposited energy is converted into soft x-rays which implode a capsule containing thermonuclear fuel. Laser plasma instabilities (LPI) determine the laser energy deposition into the hohlraum wall. In particular, forward- or side-scatter between laser beams crossing at the laser entrance holes (LEH) of the hohlraum [2–4] can lead to transfer of energy between cones of beams and affect the hohlraum radiation symmetry [5, 6], while backscatter instabilities can cause an energy loss as well as an imbalance of the energy deposited onto the wall [7].

In the 2009 hohlraum energetics experimental campaign [8] on the National Ignition Facility (NIF) [9], crossed-beam energy transfer has been used to adjust the energy balance on the hohlraum wall and achieve symmetric capsule implosions [5, 6]. On the NIF, the "inner beams", at 23.5° and 30° from the hohlraum axis and irradiating the hohlraum near its waist, are generated by a first oscillator at λ_{inner}; the "outer beams", at 44.5° and 50° from the hohlraum axis and hitting the hohlraum wall further from the capsule, have a separate oscillator at λ_{outer} (cf. Fig. 1). Increasing the wavelength separation $\Delta\lambda = \lambda_{inner} - \lambda_{outer}$ leads to energy transfer from the outer to the inner beams, which increases the energy balance towards the hohlraum waist and leads to a more prolate implosion symmetry [3, 10]. However, as $\Delta\lambda$ was tuned from 0.5 Å to 1.7 Å in these experiments [5], the hohlraum peak radiation flux dropped by 7%, while the total SRS losses (inferred from the hot electrons measurements) increased by a factor 3.4.

In this letter, we propose a new scheme based on three tunable wavelengths [11] to control the energy transfer within the inner cones of beams and reduce SRS losses, with a predicted increase from 87% to >94% in laser coupling on large scale experiments. We have developed a new integrated model that has been tested against experimental measurements of beams brightness on the hohlraum wall, capsule implosion symmetry and radiation flux on large scale NIF experiments. The model is used to analyze the three wavelength scheme, which consists in redirecting the laser energy from the 23.5° beams which are most prone to SRS, into the 30° beams. We estimate that the total SRS losses on NIF experiments can be cut by ∼2-3× while keeping a good implosion symmetry.

The model is compared to a series of shots where $\Delta\lambda$ was tuned to achieve a round implosion symmetry [5]. The targets were cryogenically cooled hohlraum emulators at 84% scale, with 4.6 mm diameter; the laser delivers a total energy of 660 kJ in a 16 ns pulse. The hohlraum was filled with pure He gas and its inner wall was coated with a mixture of Au and B. The wavelength shifts $\Delta\lambda$ quoted here are defined "on target", i.e. after frequency tripling, in accordance with Ref. [5].

Fig. 1 shows the main experimental diagnostics. The variations of laser beams brightness as they hit the hohlraum wall are measured by the static x-ray imager (SXI) [12, 13] (Fig. 1a). This diagnostic captures time-integrated images of the interior of the hohlraum wall x-ray emission at [3-5] keV through the LEH. Fig. 1b shows the gated x-ray diagnostic (GXD) [14–16] images of the capsule x-ray emission at time of peak emission (the images are integrated over 75 ps). As $\Delta\lambda$ was tuned from 0.5 to 1.7 Å, the energy transfer from the outer beams to the inner beams led to a less oblate capsule implosion [5, 6] and to a decrease of the outer beams brightness. As the backscatter losses on the outer beams were negligible (<1%), SXI provides a direct measurement of the decrease of the laser energy deposited on the hohlraum wall by the outer beams. It indicates that the outer beams energy on the wall went down by about 30% from $\Delta\lambda$=0.5 to 1.7 Å. The inner beams are not visible on the SXI; as they have half the energy of the outer beams, their relative energy increase from crossed-beam transfer can be inferred as ∼+60%.

The Dante diagnostic [17, 18], measuring the x-ray spectrum from 0 to 20 keV emitted through the LEH,

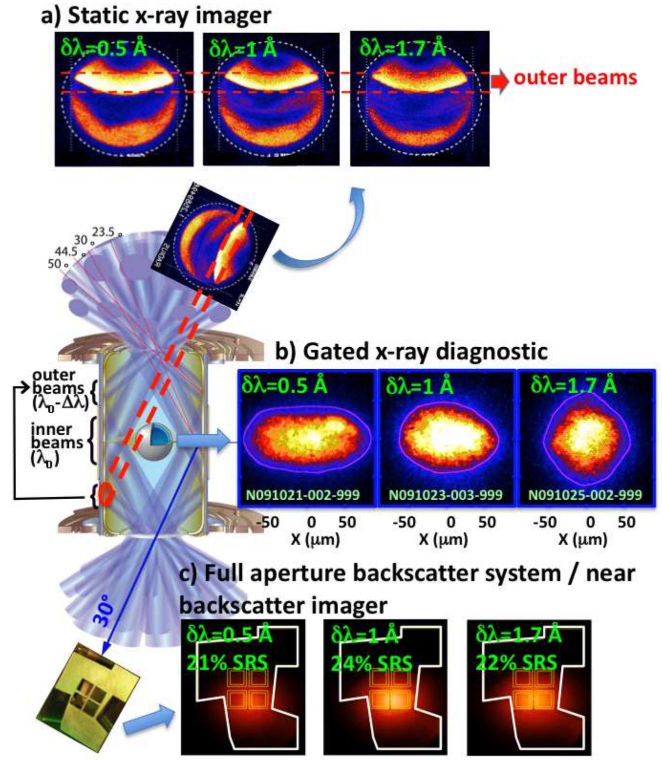

FIG. 1: NIF hohlraum and the imaging diagnostics used to correlate LPI to hohlraum energetics: a) the static x-ray imager (SXI) images the interior of the hohlraum wall through the LEH; the variations in the outer beams brightness are used to calculate the crossed-beam energy transfer; b) the gated x-ray (GXD) images show the capsule implosion symmetry; and c) the FABS/NBI system shows that the SRS on the 30° quadruplet remains nearly constant in spite of the energy transfer from the outer beams to the inner beams.

showed a reduction of the peak x-ray flux of 7% as $\Delta\lambda$ was tuned from 0.5 to 1.7 Å, indicating increasing losses in the hohlraum as more energy was transferred from the outer to the inner beams.

The FABS and NBI backscatter diagnostics are installed on two quadruplets of beams on the NIF, at 30° and 50° from the hohlraum axis [19]. Negligible backscatter (<1%) was measured on the 50° quadruplet, while the 30° quadruplet measured a nearly constant SRS backscattered energy as $\Delta\lambda$ was tuned from 0.5 to 1.7 Å despite the drop in x-ray flux measured by Dante. The time-integrated reflectivity (relative to the input energy of that 30° quarduplet) was between 21% and 24% for all three $\Delta\lambda$ (Fig. 1c); no stimulated Brillouin scattering was measured on the 30° beams.

A quantitative analysis of the FFLEX diagnostic [20–22] showed an increase in hot electrons as we increased $\Delta\lambda$. Fig. 2a shows two temperature fits of the FFLEX data for the three experiments. Each pair of points (one with Thot∼10-20 keV and another at 30-60 keV) corresponds to one particular fit; any plotted fit has each of its spectral channels voltage within 10% of the overall best fit. Using the SRS spectra measured by FABS (the average SRS wavelength was about 560 nm; the time-resolved spectra were very similar between the three shots), we infer a temperature of 17 keV for the hot electrons generated by SRS [7]. Using this temperature as a constraint on the fits, the total SRS energy loss can be estimated using the Manley-Rowe relations. This shows a strong increase of the total SRS with $\Delta\lambda$, as shown in Fig. 2b. The total SRS energy loss increases from 25.5±13 kJ for $\Delta\lambda$=0.5 Å to 87±7 kJ for $\Delta\lambda$=1.7 Å, while the 30° SRS energy stays nearly constant around 25 kJ. Additional evidence from the NBI diagnostic suggests that the increase in total SRS is coming from the undiagnosed 23.5° beams.

Three dimensional paraxial calculations show non-uniform intensity distributions resulting from crossed-beam transfer [10], which we believe to be the cause for the different behavior of the 23.5° and 30° beams SRS.

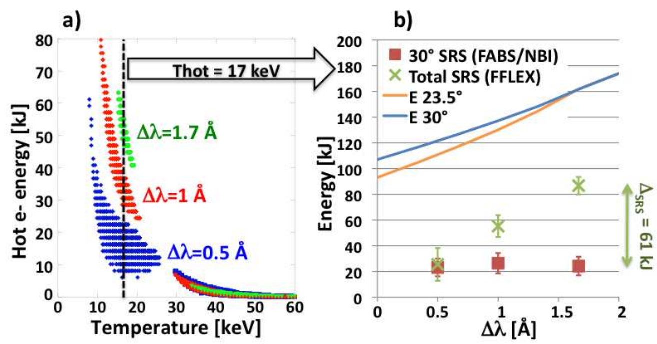

FIG. 2: a) Two-temperature fits from the FFLEX hot-electrons diagnostic maintaining a <10% error compared to the overall best fit. The 30° quadruplet SRS time-resolved spectra suggests Thot=17 keV, from which the hot electrons energy is inferred. b) Total SRS as a function of $\Delta\lambda$, calculated from the hot electron energy at 17 keV. Also shown is the 30° SRS measured from the FABS/NBI diagnostic and the total energy in the 23.5° and 30° cones after crossed-beam transfer (but before backscatter).

Fig. 2b therefore suggests that the SRS backscattered energy from the 23.5° cone increases from 2.4±14.5 kJ at $\Delta\lambda$=0.5 Å to 62.5±10 kJ at $\Delta\lambda$=1.7 Å. This corresponds to 9±2.7 % total energy loss, which is consistent with the 7.1±2.5 % drop in peak x-ray flux observed in Dante over the same wavelength range.

These experimental observations have led us to develop an integrated LPI and radiation-hydrodynamics model to understand these experiments and design the forthcoming ones. We use the Lasnex radiation-hydrodynamics code [23] with the DCA atomic physics model [24, 25] and a flux limiter f=0.15. This model brings the SRS and SBS spectra calculated using linear gains with the LIP code [26] in good agreement with those measured by FABS. This observation validates the electron density and temperature modeling of the interior of the hohlraum. In NIF size hohlraums, a higher emissivity model leads to higher plasma emissivities, reducing the energy deposited in the coronal plasma and increasing soft x-ray fluxes measured by Dante in accordance with experimental measurements [27, 28]. A high flux limiter provides results that are consistent with non-local heat transport calculations. A crossed-beam energy transfer model simultaneously calculates linear kinetic couplings between all of the 24 quadruplets of beams crossing at the LEH [6]. The ion acoustic waves are calculated with a constant "ad-hoc" saturation level $\delta n/n = 3 \times 10^{-4}$, matching the experimental data on several shots with various hohlraum sizes, laser pulse shapes and energies. The measured backscatter is removed from the simulations input laser power after the energy transfer is applied. For the 30° cone, we use the measured time-history of SRS; for the 23.5° , we use the inferred SRS calculated from the FFLEX measurements.

The results are shown in Fig. 3. The simulated SXI, GXD and Dante show a very good agreement with the experiments. At 0.5 Å, our model predicts negligible crossed-beam transfer (+1.5% towards the outer cones), but an oblate implosion as observed in the experiments, due to the inner beams SRS and absorption in the cold plasma (T_e <2 keV around the capsule). The cone fraction, defined as the ratio of the inner cone energy to the total energy (after energy transfer and LPI losses), needs to be about 40-45% in order to obtain a round implosion. As $\Delta\lambda$ is increased to 1.7 Å, the ∼60% energy increase of the inner beams from crossed-beam transfer leads to the required cone fraction for symmetric implosion; however, the increased laser energy deposition in the plasma and the increase in SRS reduce the total laser energy reaching the hohlraum wall, resulting in the drop in x-ray flux.

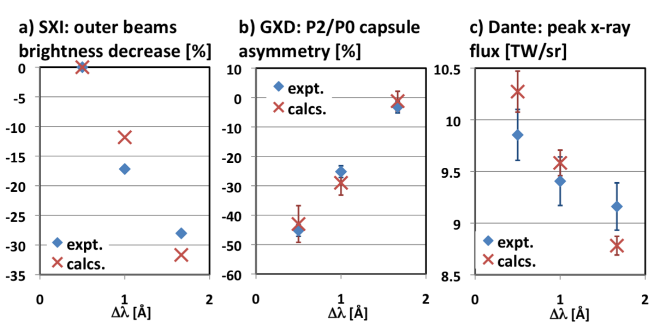

FIG. 3: Simulated vs. measured hohlraum observables: a) outer beams brightness from SXI (relative units); b) P2/P0 (pole-waist) asymmetry from GXD; c) peak x-ray flux from Dante. The error bars on the simulation results for GXD and Dante are calculated using the uncertainty on the inner beams total SRS measured with FFLEX.

The different behavior between the 23.5° and 30° cones has led us to implement a third laser wavelength option on NIF. The third oscillator will seed the 23.5° cone, separately from the 30° cone and the outer cones. We will have two tunable wavelength separations: $\Delta\lambda_{out} = \lambda_{44.5,50} - \lambda_{30}$ and $\Delta\lambda_{23.5} = \lambda_{23.5} - \lambda_{30}$. Note that a NBI diagnostic is also under development on a 23.5° quadruplet.

The effect of shifting $\Delta\lambda_{23}$ while keeping $\Delta\lambda_{out}$ fixed at 1.7 Å is shown in Fig. 4a. If the 23.5° and 30° have the same wavelength (i.e. $\Delta\lambda_{23}$=0), they can only exchange energy if there is a flow pattern that can Doppler-shift their beat wave. Since these beams are azimuthally clocked on NIF, that would require an azimuthal flow, which is negligible in hohlraum targets where the flow is essentially axisymmetric [10]. On the other hand, if a wavelength separation is introduced between these beams, then the transfer becomes larger than between an inner and an outer beam with a similar shift due to a much larger overlap volume. Therefore, shifting $\Delta\lambda_{23}$ introduces significant energy transfer from the 23.5° cone to the 30° while the outer cones stay nearly constant, as seen in Fig. 4a. This means that we can redistribute the energy between the two inner cones with minor impact on the outer cones; we have also shown that the cone fraction can be finely readjusted by a small change in $\Delta\lambda_{out}$ if needed. Three-dimensional simulations of 6 quadruplets of NIF beams have showed that the distortion in the 30° beams intensity distribution is similar between a $\Delta\lambda_{23}$ and a $\Delta\lambda_{out}$ tuning, suggesting that the 30° beams SRS losses should not increase with $\Delta\lambda_{23}$.

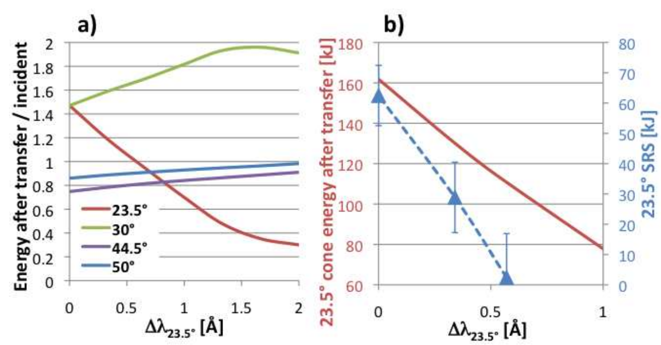

FIG. 4: a) Ratio of energy after to before crossed-beam transfer for each cone of beams as a function of $\Delta\lambda_{23}$, for a fixed $\Delta\lambda_{out}$=1.7 Å. b) Red solid line: energy in the 23.5° cone after crossed-beam transfer as a function of $\Delta\lambda_{23}$, for a fixed $\Delta\lambda_{out}$=1.7 Å. Blue triangles: corresponding SRS energy from the 23.5° cone, inferred from the experimental observations (cf. Fig. 2b).

The strategy is to tune $\Delta\lambda_{23}$ to transfer enough energy from the 23.5° beams into the 30° to drop the 23.5° energy below the SRS threshold (i.e. below 110 kJ, per Fig. 2b). Fig. 4b shows that this should be achieved for $\Delta\lambda_{23}$>0.6 Å. If we further assume that the 30° SRS energy loss will stay constant with energy transfer, we should then recover the 7% loss in drive due to SRS on the 23.5° when going from $\Delta\lambda$=0.5 to 1.7 Å (Fig. 3c), while preserving the overall symmetry (P2/P0∼0) since the cone fraction would not be significantly affected.

In summary, we have presented and analyzed a new scheme to limit the SRS losses in NIF experiments. A new hydrodynamics/laser plasma interaction model has been developed, and matches the experimental results on crossed-beam energy transfer, hohlraum drive and capsule implosion symmetry. Detailed analysis of the 2009 National Ignition Campaign experiments suggests that the 23.5° beams SRS is more sensitive to the laser energy after transfer than the 30° SRS which basically stays constant regardless of energy transfer. A third wavelength option can transfer energy from the 23.5° into the 30° beams while keeping the outer beams nearly constant due to the flow structure inside the hohlraums. Our hydrodynamics/LPI integrated model estimates that a wavelength shift of the order of one ångström between the 23.5° and 30° beams can significantly reduce the total SRS and increase the radiation drive in the hohlraum while keeping a good implosion symmetry. This scheme will be tested on the upcoming NIF experiments at the MJ scale.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

[1] J. D. Lindl, P. Amendt, R. L. Berger, S. G. Glendinning, S. H. Glenzer, S. W. Haan, R. L. Kauffman, O. L. Landen, and L. J. Suter, Phys. Plasmas **11**, 339 (2004).
[2] W. L. Kruer, S. C. Wilks, B. B. Afeyan, and R. K. Kirkwood, Phys. Plasmas **3**, 382 (1996).
[3] P. Michel, L. Divol, E. A. Williams, S. Weber, C. A. Thomas, D. A. Callahan, S. W. Haan, J. D. Salmonson, S. Dixit, D. E. Hinkel, et al., Phys. Rev. Lett. **102**, 025004 (2009).
[4] R. K. Kirkwood, B. B. Afeyan, W. L. Kruer, B. J. MacGowan, J. D. Moody, D. S. Montgomery, D. M. Pennington, T. L. Weiland, and S. C. Wilks, Phys. Rev. Lett. **76**, 2065 (1996).
[5] S. H. Glenzer, B. J. MacGowan, P. Michel, N. B. Meezan, L. J. Suter, S. N. Dixit, J. L. Kline, G. A. Kyrala, D. K. Bradley, D. A. Callahan, et al., Science **327**, 1228 (2010).
[6] P. Michel, S. H. Glenzer, L. Divol, D. K. Bradley, D. Callahan, S. Dixit, S. Glenn, D. Hinkel, R. K. Kirkwood, J. L. Kline, et al., Phys. Plasmas **17**, 056305 (2010).
[7] W. L. Kruer, *The physics of laser plasma interactions* (Westview Press, 2003).
[8] N. B. Meezan, L. J. Atherton, D. A. Callahan, E. L. Dewald, S. Dixit, E. G. Dzenitis, M. J. Edwards, C. A. Haynam, D. E. Hinkel, O. S. Jones, et al., Phys. Plasmas (2010).
[9] E. I. Moses, R. N. Boyd, B. A. Remington, C. J. Keane, and R. Al-Ayat, Phys. Plasmas **16**, 041006 (2009).
[10] P. Michel, L. Divol, E. A. Williams, C. A. Thomas, D. A. Callahan, S. Weber, S. W. Haan, J. D. Salmonson, N. B. Meezan, O. L. Landen, et al., Phys. Plasmas **16**, 042702 (2009).
[11] E. I. Moses, private communication, LLNL, 04/29/2010.
[12] M. D. Landon, J. A. Koch, S. S. Alvarez, P. M. Bell, F. D. Lee, and J. D. Moody, Rev. Sci. Instrum. **72**, 698 (2001).
[13] M. B. Schneider, O. S. Jones, N. Meezan, J. L. Milovich, R. P. Town, S. S. Alvarez, R. G. Beeler, D. K. Bradley, J. R. Celeste, S. N. Dixit, et al., Rev. Sci. Instrum. (2010).
[14] G. A. Kyrala, J. Oertel, T. Archuleta, and J. Holder, in *Proc. SPIE*, edited by A. M. Khounsary, C. Morawe, and S. Goto (2009), vol. 7448, p. 74480S.
[15] J. A. Oertel, R. Aragonez, T. Archuleta, C. Barnes, L. Casper, V. Fatherley, T. Heinrichs, R. King, D. Landers, F. Lopez, et al., Rev. Sci. Instrum. **77**, 10E308 (2006).
[16] G. A. Kyrala, S. Dixit, S. Glenzer, D. Kalantar, D. Bradley, M. Izumi, N. Meezan, O. L.Landen, D. Callahan, S. V. Weber, et al., Rev. Sci. Instrum. (2010), accepted for publication.
[17] H. N. Kornblum, R. L. Kauffman, and J. A. Smith, Rev. Sci. Instrum. **57**, 2179 (1986).
[18] E. L. Dewald, K. M. Campbell, R. E. Turner, J. P. Holder, O. L. Landen, S. H. Glenzer, R. L. Kauffman, L. J. Suter, M. Landon, M. Rhodes, et al., Rev. Sci. Instrum. **75**, 3759 (2004).
[19] J. D. Moody, P. Datte, K. Krauter, E. Bond, P. A. Michel, S. H. Glenzer, L. Divol, C. Niemann, L. Suter, N. Meezan, et al., Rev. Sci. Instrum. (2010).
[20] E. L. Dewald, C. Thomas, S. Hunter, L.Divol, N. Meezan, S. H. Glenzer, L. J. Suter, E. Bond, J. L. Kline, J. Celeste, et al., Rev. Sci. Instrum. (2010).
[21] J. W. McDonald, R. L. Kauffman, J. R. Celeste, M. A. Rhodes, F. D. Lee, L. J. Suter, A. P. Lee, J. M. Foster, , and G. Slark, Rev. Sci. Instrum. **75**, 3753 (2004).
[22] C. L. Wang, Rev. Sci. Instrum. **52**, 1317 (1981).
[23] G. B. Zimmerman and W. L. Kruer, Comments Plasma Phys. Control. Fusion **2**, 51 (1975).
[24] Y. T. Lee, Journal of Quantitative Spectroscopy and Radiative Transfer **38**, 131 (1987).
[25] H. Scott and S. Hansen, High Energy Density Physics **6**, 39 (2010).
[26] D. J. Strozzi, E. A. Williams, D. E. Hinkel, D. H. Froula, R. A. London, and D. A. Callahan, Phys. Plasmas **15**, 102703 (2008).
[27] J. L. Kline et al., Phys. Rev. Lett. (2010), submitted.
[28] M. D. Rosen, Tech. Rep. LLNL-PRES-428527 3/18/10, LLNL (2010).